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4. Title of the invention

A Semiconductor Laser Device

5. Name of your agent *(if you have one)*

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A Semiconductor Laser Device

This invention relates to a semiconductor laser device and particularly, but not exclusively, to a semiconductor laser device that emits visible radiation in the wavelength range 630nm to 680nm. The laser device may be of the edge-emitting or of the surface-emitting type.

Laser devices or laser diodes (LDs) fabricated in the (Al,Ga,In)P material system which emit visible light in the 630nm-680nm wavelength range are becoming increasingly important components of professional and consumer products. For example, it is envisaged that the Digital Video Disc (DVD) system will employ a 635nm-650nm wavelength LD capable of delivering up to 30mW output power up to a temperature of 60°C. The next generation of semiconductor lasers will need an even greater maximum power output up to a higher (eg. 70°C) operating temperature.

By the (Al,Ga,In)P system is meant the family of compounds having the general formula $(Al_xGa_{1-x})_{1-y}In_yP$, where both x and y are between 0 and 1. One particular advantage of this semiconductor system is that it is lattice-matched to a GaAs substrate when the indium mole fraction, y, is equal to 0.48.

A principal limitation of current (Al,Ga,In)P laser diodes is that they are incapable of operating for long periods (or with a sufficiently low threshold current) at the highest specified operating temperature. It is generally believed that this is caused by electron leakage from the active region of the device into the surrounding optical guiding region and subsequently into the p-type cladding region.

The generic structure of a separate confinement laser structure intended to generate light at 630-680nm will now be described with reference to Figures 1 and 2.

Curve (a) of Figure 1 illustrates the difference between the Γ-conduction band energy of $(Al_xGa_{1-x})_{0.52}In_{0.48}P$ and $Ga_{0.52}In_{0.48}P$, as a function of the aluminium mole fraction in

the quaternary alloy. Curves (b) and (c) of Figure 1 show the difference between the X-conduction band energy and the Γ-valance band energy respectively. Figure 1 assumes that the bandgap difference between (Al,Ga)InP and GaInP is split in a ratio of 70:30 between the conduction band offset and the valance band offset.

It will be seen that the minimum energy in the conduction band of (Al,Ga,In)P is a function of the aluminium content. There is a crossover from a Γ-band minimum to an X-band minimum at an aluminium concentration of about 0.55.

The terms Γ-band and X-band as used herein refer to symmetry points in the Brillouin zone and are standard terms in solid state physics, see for example R. A. Smith "Semiconductors", (Cambridge University Press, 1978). The terms Γ-minimum and X-minimum refer to the minimum energy level of the Γ-band and the X-band, respectively.

Figure 2 is a schematic band structure of a separate confinement laser structure fabricated in the (Al,Ga,In)P system. It consists of an n-doped $(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ cladding region 1, an $(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ optical guiding region 2, 4, a GaInP quantum well active region 3 disposed within the $(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ optical guiding region, and a p-doped $(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ cladding regions. Optical transitions giving rise to laser action in the quantum well active region 3 of the laser diode originate from Γ-electrons in the GaInP quantum well active region.

The electron leakage current consists of that fraction of the electrons which have sufficient thermal energy to surmount the potential barrier on the right hand side of Figure 2, and pass into the p-doped cladding region 5. It will be seen that Γ-electrons are confined in the optical guiding region (waveguide region) by a potential barrier of only around 90meV at the interface with the p-doped cladding region. This relatively small barrier height allows a significant proportion of electrons to escape. Moreover, holes in the valence band are confined only by a potential barrier of around 50meV, and this low barrier height also allows significant carrier escape. Furthermore the X-conduction band in the p-cladding region 5 is some 50meV <u>below</u> the Γ-conduction

band in the waveguiding region 2, 4, and this allows electrons to escape from the waveguiding region 2, 4 through the X-states in the p-doped cladding regions. Thus, the laser illustrated in Figure 2 has a high leakage current, and so has poor performance at high temperatures.

P. M. Smowton et al. in "Applied Physics Letters" Vol. 67, pp. 1265-1267 (1995) show that an important leakage mechanism for electrons can be via the indirect X-valley of the conduction bands in the p-side guiding and cladding regions of a separate confinement hetero-structure laser having two $Ga_{0.41}In_{0.59}P$ quantum wells separated by a barrier, or set in an optical guiding region of $(Al_yGa_{1-y})_{0.51}In_{0.49}P$ (where y is variously 0.3, 0.4 and 0.5), and clad with $(Al_{0.7}Ga_{0.3})_{0.51}In_{0.49}P$ cladding regions, doped with Zn on the p-side and Si on the n-side. However, no proposals are made for mitigating the problems caused by loss of electrons via this mechanism.

There have been a number of proposals to improve the temperature performance of laser devices fabricated in the (Al,Ga,In)P system.

T. Takagi et al, "IEEE Journal of Quantum Electronics)" Vol 27, No. 6, 1511 (1991) have proposed introducing a multiple-quantum well barrier in the cladding region.

In UK Patent Application No. 9526631.8, it is proposed that the insertion of a δ-doped p- type layer in the p-doped cladding region of a SCH laser diode will have the effect of increasing the band bending on the p-side of the hetero-junction and thus increase the potential barrier which is presented to thermal leakage of electrons.

G. Hatakoshi et al., "IEEE Journal of Quantum Electronics, Vol. 27, p1476 (1991) have proposed increasing the doping level of the p-doped cladding region, in order to increase the potential barrier between the waveguiding region and the p-doped cladding region. UK Patent Application No. 9626644.0 discloses a semiconductor laser which incorporates an electron reflecting layer, to prevent X-electrons escaping into the p-doped cladding region. UK Patent Application No. 9626657.2 discloses the use of electron capture layers to capture X-electrons, and transfer them to a Γ-confined energy

level in the active region. However, the effectiveness of these schemes to improve the temperature characteristics of an (Al,Ga,In)P laser device is currently unclear.

The principle of operation of a multiple quantum well barrier (MQB) is to incorporate an MQB in the p-type cladding region of an SCH laser device. The MQB consists of very thin alternating layers of, for example, (In,Ga)P and (Al,Ga,In)P (for an (Al,Ga,In)P laser). An electron which has sufficient thermal energy to escape from the SCH structure will be quantum mechanically reflected at each of the interfaces of the MQB. If the layer thicknesses are chosen to be $\lambda/4$ in thickness, where λ is the electron wavelength, then a band of energies can be engineered at which electrons will be reflected with a probability of 1. Almost unity reflectivity of the electrons can be engineered to exist well above the classical barrier height. Theoretically, a MQB can increase the effective barrier height by up to a factor of 2 compared to the classical barrier height.

K. Kishino et al. "Applied Physics Letters" Vol. 58, pp 1822-1824 (1991) and H. Hamada et al "Electronics Letters" Vol. 28, pp 1834-1836 (1992) provide evidence to show that the temperature dependence of the threshold current of short wavelength lasers is improved through the use of such reflectors. However, the effectiveness of the reflectors is usually inferred from LD operating characteristics rather than from a direct measurement of the enhancement of the barrier height. It is difficult to quantify, therefore, just what advantage has accrued from the use of a MQB in comparison to any advantage that might have occurred simply due to better processing or better material quality. Furthermore, it should be noted that the effectiveness of the MQB is realised only if the coherence length of the electrons is long. Anything which destroys this coherence such as, for example, interface scattering, will significantly diminish the reflectivity properties.

Increasing the doping level of the p-doped cladding layer will increase the potential barrier between the waveguiding region 4 and the p-doped cladding region 5. However, there are practical limitations to the amount of p-doping which can be incorporated into (Al,Ga,In)P or (Al,In)P cladding regions. This is particularly true of MOCVD grown

materials, where a maximum impurity concentration of approximately 2 x $10^{18}cm^{-3}$ can be achieved using either Zn or Mg. An example of this is given by D. P. Bour et al. in "IEEE Journal of Quantum Electronics" Vol. 30, pp. 593-606 (1994). However, any further increase in the dopant concentration using this technique causes the dopant to diffuse into the active region of the device, thereby degrading its performance.

It is possible to increase the aluminium content of the cladding layer 5 in order to increase the potential barrier between the waveguiding region 4 and the p-doped cladding region 5, and thereby increase the Γ-electron and valance band hole confinement. This approach is illustrated in Figure 3. This illustrates an SCH laser structure that is similar to that shown in Figure 2, but in which the cladding regions 1,5 are formed of AlInP. The potential barrier between the optical guiding region 4 and the p-doped cladding region 5 is now 250meV, and the potential barrier confining the valence band holes is now 100meV. Thus, the laser structure shown in Figure 3 will have improved carrier confinement compared to the structure shown in Figure 2.

Increasing the aluminium content of the cladding layers 1,5 will not, however, prevent carrier escape via the X-band states in the p-doped cladding region 5.

A first aspect of the present invention provides a separate confinement heterostructure laser device comprising: an optical guiding region; an active region having at least one energy well, said active region being disposed in said optical guiding region; and n-doped and p-doped cladding regions disposed on opposite sides of the optical guiding region; wherein an electron-reflecting barrier is provided at the p-side of the active region for reflecting Γ-electrons and X-electrons.

S. J. Chang et al., "IEEE Photonics Technology Letters" Vol. 10, No. 5, p651 (1998) describes an (Al,Ga,In)P laser diode having an emission wavelength of 642nm. The laser diode is provided with a triple tensile strain barrier cladding layer to introduce a barrier to Γ-electrons. Improved temperature dependence is observed. However, the tensile reflective layers do not provide any barrier to X-electrons. On the contrary, they

introduce quantum wells for trapping X-electrons. Thus, significant carrier loss via the X-band states in the p-doped cladding region still occur with this structure.

US Patent No. 5 509 024 discloses a laser diode having a tunnel barrier layer. An AlAs barrier layer is introduced between the optical guiding region and the p-doped cladding region to act as a barrier to Γ-electrons.

US Patent No. 5 509 024 does not address the problem of carrier loss via the X-states in the p-doped cladding region. The patent proposes locating the AlAs barrier layer between a $(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ optical guiding region and a $(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ cladding region. In the light of recent experimental evidence concerning the Γ-X direct-indirect bandgap changeover, it can be seen that the structure proposed in US Patent No. 5 509 024 will introduce a 0.32eV trapping quantum well for X-electrons. Thus, while the scheme proposed in this patent will introduce a potential barrier of around 0.58eV for Γ-electrons, it will not address the problem of carrier loss via the X-states in the p-doped cladding region. Indeed, the introduction of the 0.32eV quantum well for X-electrons will aggravate this problem.

In contrast to the above prior art, however, the present invention provides a barrier that will prevent leakage of both Γ-electrons and X-electrons. The problem of carrier loss via the X-states in the p-doped cladding region is prevented, or at least significantly reduced, since the electron-reflecting barrier reflects X-electrons as well as Γ-electrons.

The electron-reflecting barrier may comprise a first electron-reflecting layer for reflecting Γ-electrons and a second electron-reflecting layer for reflecting X-electrons. This is a convenient way of providing a barrier for both Γ-electrons and X-electrons.

At least one of the electron-reflecting layers may be a strained layer. In some cases, a strained semiconductor layer has a forbidden bandgap that is greater than the forbidden bandgap of the bulk semiconductor material, and using such a strained layer as an electron-reflecting layer will increase the potential barrier to electron and hole leakage.

One of the electron-reflecting layers may be in a state of compressive strain and the other of the electron-reflecting layers may be in a state of tensile strain. The two electron-reflecting layers will thus form a strain-compensated barrier. It has been reported that a strain-compensated barrier can be made thicker than the sum of the critical thicknesses of the individual layers without introducing defects into the layers. This means that a strain compensated electron-reflecting barrier can be made thicker without introducing defects, and a thicker barrier will reflect more electrons back into the active region thereby improving the confinement of the electrons.

The layer for reflecting Γ-electrons may be disposed between the optical guiding region and the layer for reflecting X-electrons. The Γ-conduction band of the optical guiding region may be substantially degenerate with the X-conduction band of the layer for reflecting Γ-electrons. This ensures that the layer for reflecting Γ-electrons does not produce a quantum well for X-electrons.

Alternatively, the layer for reflecting Γ-electrons may be disposed between the layer for reflecting X-electrons and the p-doped cladding region. In this arrangement, the formation of a quantum well for X-electrons in the layer for reflecting Γ-electrons does not cause a serious problem, since few X-electrons reach the layer for reflecting Γ-electrons. This arrangement therefore allows a wider choice of materials for the optical guiding region.

The electron-reflecting barrier may comprise a plurality of first electron-reflecting layers for reflecting Γ-electrons and a plurality of second electron-reflecting layers for reflecting X-electrons. The electron reflecting barrier may be a superlattice structure. This is possible because the electron barrier is strain compensated.

The laser device may be fabricated in the (Al,Ga,In)P system, the or each layer for reflecting Γ-electrons may be AlP or GaP, and the or each layer for reflecting X-electrons may be InP. This provides a convenient way of reducing the leakage current in an (Al,Ga,In)P laser.

The layer for reflecting Γ-electrons may be AlP and the optical guiding region may be $(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$. This makes the Γ-conduction band of the optical guiding region substantially degenerate with the X-conduction band of the layer for reflecting Γ-electrons, as is preferable when the layer for reflecting Γ-electrons is disposed between the optical guiding region and the layer for reflecting X-electrons.

The thickness of each of the electron-reflecting layers may be 16Å or less. This thickness is lower than the critical thickness at which the formation of misfit dislocations in a strained layer becomes energetically favourable.

At least one of the electron-reflecting layers may be p-doped. If the electron-reflecting layers are heavily p-doped band bending will occur, and this will increase the height of the potential barrier to electron transport into the p-cladding region. The p-doping will also reduce the barrier height for hole transport into the optical guiding region.

The first electron-reflecting layer, or at least one of the first electron-reflecting layers (if there are more than one), may contain indium. Introducing indium into an AlP or GaP strained layer will reduce the strain in the layer, and will hence increase the critical thickness of the layer. The layer(s) for reflecting Γ-electrons can therefore be made thicker, and this will reduce the probability that electrons can tunnel through the layer.

The electron-reflecting barrier may be disposed between the optical guiding region and the p-doped cladding region.

A second aspect of the present invention provides a separate confinement heterostructure laser device comprising: an optical guiding region; an active region having at least one energy well, said active region being disposed in said optical guiding region; and n-doped and p-doped cladding regions disposed on opposite sides of the optical guiding region; wherein an electron-reflecting layer for reflecting Γ-electrons is disposed at the p-side of the active region; and wherein the Γ-conduction band of the

optical guiding region is substantially degenerate with the X-conduction band of the electron-reflecting layer.

This aspect of the present invention addresses the problem outlined above with reference to the lasers described in S. J. Chang et al. and in US Patent No. 5 509 024. In this aspect, the X-conduction band of the electron reflecting layer is chosen to be substantially degenerate with the Γ-conduction band of the optical guiding region. This prevents the formation of a quantum well for X-electrons in the layer for reflecting Γ-electrons. This can be done, for example, by selecting the composition of the optical waveguiding region appropriately.

The optical guiding region may be formed of $(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$, and the electron-reflecting layer may be formed of AlP. This is a convenient way of putting the second aspect of this invention into practice in the (Al,Ga,In)P system.

The electron-reflecting layer may be p-doped.

The electron-reflecting layer may be disposed between the optical guiding region and the p-doped cladding region.

Preferred embodiments of the present invention will now be described in detail by way of illustrative examples with reference to the accompanying Figures in which:

Figure 1 shows the variation in the (Ga,In)P/(Al,Ga,In)P heterobarrier height as a function of the aluminium mole fraction of the quaternary alloy;

Figure 2 is a schematic band structure diagram of a separate confinement hetrostructure semiconductor laser fabricated in the (Al,Ga,In)P system;

Figure 3 is a schematic band structure diagram of a SCH laser similar to that shown in Figure 2, but in which the cladding layers are formed of (Al,In)P;

Figure 4 is a schematic band diagram of an SCH laser according to a first embodiment of the present invention;

Figure 5 is a schematic diagram of the band structure of the optical guiding region and p-type cladding region of an SCH laser diode containing an electron reflecting barrier layer according to a further embodiment of the present invention;

Figure 6 illustrates the band structure of a modification of the embodiment of Figure 5;

Figure 7 illustrates the schematic band structure diagram of a further modification of Figure 5;

Figure 8 shows the schematic band structure of a modification of Figure 6; and

Figure 9 is a partial view of the conduction band of Figure 5.

Figure 4 is a schematic illustration of the band structure of a first embodiment of the invention. This shows the band structure of the optical guiding region and the p-doped cladding region 11 of a SCH laser device.

The embodiment of Figure 4 is fabricated in the (Al,Ga,In)P system. The optical guiding region 10 is formed of $(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$. The cladding region is formed of $(Al_xGa_{1-x})_{0.52}In_{0.48}P$, where $0.5< x \leq 1.0$. In this embodiment x is chosen to be 1, so the cladding layer 5 is $Al_{0.52}In_{0.48}P$. An electron-reflecting layer 12, formed of AlP, is disposed between the optical guiding region 10 and the p-doped cladding region 11.

The lattice constant for AlP is 5.467Å, whereas the lattice constant of the optical guiding region 10 will be 5.653Å. (As noted above, (Al,Ga,In)P having an indium mole fraction of 0.48 is lattice matched to GaAs, so that the lattice constant of the optical guiding region will be equal to the lattice constant of GaAs.) The lattice constant of the cladding region 11 will also be 5.653Å since the cladding region has an indium mole

fraction of 0.48. Thus, the lattice mismatch between the electron-reflecting layer 12 and the optical guiding region 10 is approximately 3.4%.

In general, dislocations would occur at an interface between two semiconductor materials having a lattice mismatch of 3.4%. This is undesirable in the present case, since these dislocations and defects would degrade the properties of the laser device.

It is well known that if the lattice mismatch between an underlying layer and a growing epilayer is sufficiently small, the first atomic layers which are deposited will be strained to match the lattice constant of the underlying layer so that a coherent interface will be formed. However, as the thickness of the growing epilayer increases, the homogeneous strain energy increases until a critical thickness is reached at which it becomes energetically favourable for misfit dislocations to be introduced. The existence of this critical thickness was first disclosed in J. H. Van der Merwe "Journal of Applied Physics" Vol. 34, page 123 (1962). It is preferable that the thickness of the electron reflecting layer 12 is lower than the critical thickness, to prevent dislocations occurring. In this case, the electron-reflecting layer will be in a strained state. In this embodiment it will be in a state of tensile strain, since AlP has a lower lattice constant than the waveguiding region 10.

For a lattice mismatch of 3.4%, the critical thickness at which misfit dislocations will occur is estimated to be 16Å, see R. People et al., "Applied Physics Letters" Vol. 47 No. 3 pp.322-324 (1985). In the embodiment of Figure 4, therefore, the thickness of the electron reflecting layer 12 is preferably 16Å or less.

In bulk AlP, the Γ-Γ bandgap is 3.6eV, and the Γ-X bandgap is 2.5eV. In the embodiment of Figure 4, however the AlP layer 12 is under tensile strain and this will reduce the bandgap from the bulk value of 3.6eV. The bandgap will be reduced to 3.295eV for the light hole and 3.5eV for the heavy hole valence band. The reduction in bandgap of a strained layer is described in, for example, Chin-Yu Yeh et al, "Physical Review B" Vol. 50, No. 4, pp2715-2718 (1994). Assuming a 70:30 band offset, the AlP electron reflecting layer therefore introduces a 0.801eV barrier to the transport of Γ-

electrons into the p-doped cladding region 11 (this calculation uses the light-hole bandgap). The X-band in the optical guiding region 10 is 0.15eV above the Γ-band, so that most electrons in the optical guiding region will be in the Γ-band. These Γ-electrons will be reflected back into the active region by the electron reflecting layer 12. A simple calculation of the transmission of an electron through a rectangular barrier indicates that only approximately 6% of Γ-electrons would be transmitted through the bottom of a 0.801eV potential barrier having a thickness of 16Å (this calculation assumes that the effective mass of the Γ-electrons is $m_0 = 0.15$). In practice, the electron transmission through the electron-reflecting layer in Figure 4 is probably less than 6%, owing to the presence of the thick p-doped cladding region 11 adjacent to the electron reflecting layer. The p-doped cladding region 11 is formed of $(Al_xGa_{1-x})_{0.52}In_{0.48}P$, where $0.5 < x \leq 1.0$, and will have a Γ-Γ bandgap of up to 2.7eV. The transmission through the AlP layer increases to approximately 13% at an energy degenerate with the Γ-band in the cladding region.

The light hole is reduced in energy compared to the heavy hole valence band in the AlP layer 12, because the layer is under tensile strain. The conduction band-light hole bandgap is 3.294eV, and this will give a potential barrier for light holes of 0.178eV. There is an approximately 26% probability of holes tunnelling through this barrier into the optical guiding region 10.

The conduction band - heavy hole bandgap in the AlP layer 12 is 3.497eV, producing a 0.239eV barrier to heavy holes (the heavy hole barrier is not shown in Figure 4).

(It should be noted that the value of the Γ-Γ bandgap in AlP may be larger (4.4eV) than the value given above, as suggested by Chin-Yu Yeh et al, and that the band offset for compressively strained layers may be 85:15 rather than 70:30, as suggested by M.D.Dawson et al, "Applied Physics Letters", Vol 64 (7) p892 (1994). Both these effects would tend to increase the potential barrier set up in Figure 4.)

In the embodiment shown in Figure 4, the aluminium concentration in the optical waveguiding region has been selected so that the Γ-band in the optical guiding region

10 is degenerate with the X-band in the AlP layer 12. This prevents a quantum well for X-electrons forming in the AlP layer, and thus overcomes the problems identified above with the devices proposed by Chang et al and US Patent No. 5 509 024.

Furthermore, for an AlInP cladding region, the X-band of the p-doped cladding region 11 in Figure 4 is 0.06eV higher than the X-band in the AlP layer 12 (if the cladding region has a lower aluminium mole fraction, the X-band potential will be lower). The few X-electrons in the optical guiding region 10 will thus face a 0.06eV potential barrier to transport into the p-doped cladding region, and this will tend to confine them within the waveguiding region. It can thus be seen that the structure illustrated in Figure 4 provides a barrier for both Γ-electrons and X-electrons.

In contrast, in the conventional structure illustrated in Figure 3, the X-conduction band in the p-doped cladding region is lower than the X-band in the optical guiding region. In the conventional structure, therefore, there is no potential barrier preventing X-electrons passing from the optical guiding region into the cladding region.

A further embodiment of the invention is illustrated in Figure 5. This figure again shows the bandgap for part of the structure of an SCH laser diode fabricated in the (Al,Ga,In)P system lattice matched to GaAs. Figure 9 shows the band energies for the optical guiding region 10 and the p-doped cladding region 11.

In this embodiment, a strain compensated barrier layer 14 is placed at the interface between the waveguiding region and the p-doped cladding region. The strain compensated barrier layer consists of an AlP layer 12 and an InP layer 13.

The AlP layer 12 and the InP layer 13 are both selected to have a thickness less than the critical thickness, to prevent misfit dislocations occurring. The AlP layer 12 and the InP layer 13 are therefore both under strain. As noted above, in connection with Figure 4, the AlP layer 12 is in a state of tensile strain, since its lattice constant is approximately 3.4% lower than the lattice constant of the optical guiding region 10 (which is lattice matched to GaAs and so has a lattice constant of 5.653Å). The InP layer, however, is in

a state of compressive strain, since its lattice constant is approximately 3.8% greater than the lattice constant of the optical guiding region 10.

For the case of a layer in a state of compressive strain, the Γ-bandgap increases whereas the X-bandgap decreases. The valence band degeneracy is split, with the heavy hole band being at a lower energy than the light hole band.

As noted above with reference to Figure 4, the AlP layer 12 provides a potential barrier of 0.801eV to Γ-electrons in the optical guiding region 10.

The thickness of the InP layer is chosen such that the first confined state in the InP layer lies above the X-band in the p-doped cladding region 11, and also lies above the X-band in the AlP layer 12. The InP layer thus acts as an additional electron reflecting layer to electrons that manage to pass through the AlP layer. It provides a 0.275eV potential barrier to X-electrons in the optical guiding region 10. The InP layer 13 thus prevents the loss of electrons from the optical guiding region 10 via X-states in the cladding region 11.

It is preferred that the aluminium content of the optical guiding region 10 is selected such that the Γ-band in the optical guiding region 10 is degenerate with the X-band in the AlP layer 12, in order to prevent a quantum well for X-electrons being set up in the AlP layer 12. To achieve this, the optical guiding region is preferably formed of $(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$.

The p-doped cladding layer 11 in Figure 5 is formed of $(Al_xGa_{1-x})_{0.52}In_{0.48}P$, where $0.5 < x \leq 1.0$ and preferably $0.7 < x < 1.0$.

Figure 9 illustrates the conduction band of the structure of Figure 5.

Γ-electrons having an energy E_0 - that is, which are at the conduction band energy of the optical guiding region 10 will encounter an 0.801eV potential barrier which has a thickness of 16Å. As noted above with reference to Figure 4, only around 6% of Γ

electrons will be transmitted through the bottom of such a barrier (assuming an effective mass $m_0 = 0.15$). (In reality, there will be almost no Γ-electron loss at the conduction band energy of the optical guiding region, due to the presence of the thick p-doped cladding region 11.)

X-electrons having an energy E_0 face a 0.275eV potential barrier provided by the InP layer 14. Approximately 6% of X-electrons having an energy E_0 will be transmitted through this barrier, assuming an effective mass $m_0 = 0.45$.

The energy E_1 shown in Figure 9 is equal to the Γ-band of the p-type cladding region 11. In a conventional SCH laser structure, such as that shown in Figure 2 for example, electrons in the optical guiding region having energy E_1 would not be confined. The probability that these electrons would be transmitted from the optical guiding region 10 into the p-type cladding layer 11 would be unity, and these electrons would be lost. In the present invention, however, Γ-electrons having an energy of E_1 face a potential barrier of 0.526eV, as a result of the AlP layer 12. Approximately 87% of Γ-electrons at energy E_1 will be reflected back into the waveguide region 10 by the AlP layer 12, and only 13% of the electrons will escape from the optical guiding region 10 into the p-type cladding region 11. This improved confinement will improve the efficiency and high temperature operation of the laser diode.

A further advantage of the invention is that the barrier layer 14 is strain compensated, since it is formed of one layer that is under tensile strain and one layer that is under compressive strain. Since the barrier layer 14 is strain compensated, it is possible to provide two or more barrier layers so as to further improve the confinement of electrons in the optical guiding region 10. It would also be possible to provide a AlP/InP superlattice barrier layer.

There is a further possible advantage of using a strain-compensated barrier layer 14. As noted above, a strained layer has a critical thickness above which misfit dislocations will occur. It has been reported, however, that a strain compensated barrier layer can be made thicker than the sum of the critical thicknesses of each individual layer without

introducing defects into the layers. That is, it may be possible to grow a strain compensated AlP/InP barrier layer that is thicker than the combination of the critical thickness of AlP and the critical thickness of InP, without causing dislocations to form. If a thicker electron-reflecting barrier can be grown without introducing defects, it will reflect more electrons back into the optical guiding region, and thus improve confinement of the electrons.

A further embodiment of the invention is illustrated in Figure 6. This is generally similar to the embodiment of Figure 5, except that the InP layer 14 is located between the optical guiding region 10 and the AlP layer 12.

In this embodiment, the InP layer 13 is made sufficiently thin so that the first confined state is located at the top of the potential well formed in the Γ-band.

In this embodiment, X-electrons in the optical waveguiding region 10 face a 0.275eV potential barrier presented by the InP layer. As noted above in connection with Figure 9, only around 6% of X-electrons will be transmitted through such a barrier. In consequence, the possible formation of a quantum well for X-electrons in the AlP layer 12 is less important. There is thus no need to select the composition of the optical guiding region 10 such that its Γ-band is degenerate with the X-band in the AlP layer 12. This provides a greater freedom in designing the structure of the LD. In particular, the aluminium content of the optical guiding region 10 can be increased, up to an x value of approximately 0.5.

In the embodiment illustrated in Figure 6, the optical guiding region 10 is formed of $(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$. In consequence, the potential barrier for Γ-electrons is 0.75eV.

A further advantage of the embodiment of Figure 6 is that there is no quantum well on the p-doped cladding region side of the barrier layer 14 that is likely to trap holes. Holes that are injected over the potential barrier presented by the AlP layer 12 are likely to "overshoot" the quantum well formed by the InP layer 13 and enter the optical guiding region 10.

A further embodiment of the invention is shown in Figure 7. This is generally similar to the embodiment of Figure 5, except that the AlP layer 12 of Figure 5 is replaced by a GaP layer 15. The barrier layer 14 in this embodiment is formed of the GaP layer 15 and a InP layer 13.

Bulk GaP has a Γ-Γ bandgap of 2.9eV and a Γ-X bandgap of 2.3eV. GaP has a lattice constant of 5.451eV, giving a lattice mismatch of around 3.7% compared to GaAs. Thus, the GaP layer 15 in Figure 8 will be in a state of tensile strain. This tensile strain will reduce the Γ-Γ bandgap of the GaP layer 15 below the value for bulk GaP, but will increase the Γ-X bandgap.

As with the previous embodiments, the thickness of the GaP layer 15 must be lower than the critical thickness at which misfit dislocations occur. This critical thickness will again be around 16Å.

An advantage of the use of GaP in place of AlP is that holes in the valence band face a lower potential barrier. Figure 7 shows that the potential barrier for holes is 0.124eV, compared to 0.178eV in Figure 5 and 6. The hole transmission probability for a 0.124eV barrier having a thickness of 16Å is around 33%.

One possible disadvantage of the structure of Figure 7 is that the potential barrier for Γ-electrons in the optical guiding region 10 is lower than in Figure 5. As shown in Figure 7, if a GaP layer is used, the potential barrier for a Γ-electron is 0.465eV, as compared to 0.801eV for an AlP layer. A 0.465eV potential barrier having a thickness of 16Å gives a transmission probability of around 11%, assuming an effective mass $m_0 = 0.15$. As noted above, however, the probability of a Γ-electron being transmitted into the p-doped cladding region is probably significantly less than this calculated value, since there is a thick (AlGa)InP layer, with a Γ-Γ bandgap of up to 2.7eV adjacent to the barrier layer 14.

An electron in the waveguide region 10 whose energy is degenerate with the Γ-band of the cladding region 11 has a probability of approximately 18% of passing through the barrier layer 14 into the cladding region 11

In this embodiment, it is preferable to select the aluminium composition of the optical guiding region 10 such that its Γ-band is degenerate with the X-band in the GaP layer, to prevent formation of a quantum well for trapping X-electrons. In the embodiment of Figure 7, this is done by choosing the aluminium mole fraction, x, of the optical guiding region 10 to be $x = 0.4$.

A further embodiment of the invention is illustrated in Figure 8. This is similar to that of Figure 7, but the InP layer 13 is placed between the GaP layer 15 and the optical guiding region 10. Thus, this embodiment corresponds to the embodiment of Figure 6, but with the AlP layer 12 of Figure 6 replaced by a GaP layer 15.

For the reasons described above with reference to Figure 6, it is not necessary for the Γ-band in the optical guiding region 10 to be degenerate with the X-band in the GaP layer 15. This means that the aluminium concentration of the optical guiding region can be chosen more freely than the aluminium concentration of the optical guiding region 10 in the embodiment of Figure 7. In the embodiment of Figure 8, the optical guiding region is formed of $(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$. For an optical guiding region 10 having this composition, most of the electrons will be located in the Γ-band, and will face a 0.465eV potential barrier against transmission into the p-doped cladding region 11. X-electrons in the optical guiding region 10 will face a 0.29eV potential barrier, owing to the presence of the InP layer. The potential barrier in the valence band to hole injection is 0.124eV. As in the embodiment of Figure 6, holes that overcome the potential barrier formed by the GaP layer 15 are likely to be swept into the waveguide region 10, and will thus "overshoot" the quantum well in the valence band formed by the InP layer 13.

In the embodiments described above, the electron reflecting layers 12, 13 and 15 are undoped. It is, however, possible for these layers to be heavily p-doped. Doping the electron reflecting layers will cause band bending, and this band bending will increase

the height of the potential barrier to electron transport from the optical guiding region 10 to the p-type cladding region 11. Doping the barrier layers p-type will also reduce the barrier height for hole transport into the optical guiding region.

The present invention has been described with reference to the (Al,Ga,In)P alloy system. The present invention, however, is not limited to this particular alloy system. A person skilled in the art of semiconductor physics and electronic materials will readily appreciate that the present invention is applicable to any hetrostructure laser device whose constituents have a conduction band dependence similar to that shown in Figure 1.

In the embodiments described above, the electron-reflecting layers 12, 13, 15 have been placed at the interface between the optical guiding region 10 and the p-doped cladding region 11. It is not, however, essential for the electron-reflecting layers to be placed exactly at the interface between the optical guiding region and the p-doped cladding region. In principle, the electron-reflecting layer(s) could be disposed within the optical guiding region 10, in the p-side of the optical guiding region. Moreover, the electron-reflecting barrier layer(s) could in principle, be placed within the p-doped cladding region, near the interface with the optical guiding region. This is, however, less preferable, since once electrons have passed into the p-doped cladding region electron loss can occur via the X-states in the cladding region even if there is a potential barrier in the Γ-band within the cladding region.

CLAIMS:

1. A separate confinement heterostructure laser device comprising:

an optical guiding region;

an active region having at least one energy well, said active region being disposed in said optical guiding region; and

n-doped and p-doped cladding regions disposed on opposite sides of the optical guiding region;

wherein an electron-reflecting barrier is provided on the p-side of the active region for reflecting both Γ-electrons and X-electrons.

2. A laser device as claimed in claim 1 wherein the electron-reflecting barrier comprises a first electron-reflecting layer for reflecting Γ-electrons and a second electron-reflecting layer for reflecting X-electrons.

3. A laser device as claimed in claim 1 wherein at least one of the electron-reflecting layers is a strained layer.

4. A laser device as claimed in claim 3 wherein one of the electron-reflecting layers is in a state of compressive strain and the other of the electron-reflecting layers is in a state of tensile strain.

5. A laser device as claimed in claim 1, 2, 3 or 4 wherein the layer for reflecting Γ-electrons is disposed between the optical guiding region and the layer for reflecting X-electrons.

6. A laser device as claimed in claim 5 wherein the Γ-conduction band of the optical guiding region is substantially degenerate with the X-conduction band of the layer for reflecting Γ-electrons.

7. A laser device as claimed in claim 1, 2, 3 or 4 wherein the layer for reflecting Γ-electrons is disposed between the layer for reflecting X-electrons and the p-doped cladding region.

8. A laser device as claimed in claim 4 wherein the electron-reflecting barrier comprises a plurality of first electron-reflecting layers for reflecting Γ-electrons and a plurality of second electron-reflecting layers for reflecting X-electrons.

9. A laser device as claimed in claim 8 wherein the electron-reflecting barrier is a superlattice structure.

10. A laser device as claimed in any preceding claim wherein the laser device is fabricated in the (Al,Ga,In)P system, the or each layer for reflecting Γ-electrons is AlP or GaP, and the or each layer for reflecting X-electrons is InP.

11. A laser device as claimed in claim 10 when dependent from claim 6 wherein the layer for reflecting Γ-electrons is AlP and the optical guiding region is $(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$.

12. A laser device as claimed in claim 10 or 11 wherein the thickness of each of the electron-reflecting layers is 16Å or less.

13. A laser device as claimed in any preceding claim wherein at least one of the electron-reflecting layers is p-doped.

14. A laser device as claimed in claim 10 or 11 wherein the first electron-reflecting layer, or at least one of the first electron-reflecting layers, contains indium.

15. A laser device as claimed in any preceding claim wherein the electron-reflecting barrier is disposed between the optical guiding region and the p-doped cladding region.

16. A separate confinement heterostructure laser device comprising:

an optical guiding region;

an active region having at least one energy well, said active region being disposed in said optical guiding region; and

n-doped and p-doped cladding regions disposed on opposite sides of the optical guiding region;

wherein an electron-reflecting layer for reflecting Γ-electrons is provided at the p-side of the active region; and

wherein the Γ-conduction band of the optical guiding region is substantially degenerate with the X-conduction band of the electron-reflecting layer.

17. A laser device as claimed in claim 16 wherein the optical guiding region is formed of $(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$, and the electron-reflecting layer is formed of AlP.

18. A laser device as claimed in claim 16 or 17 wherein the electron-reflecting layer is p-doped.

19. A laser device as claimed in claim 16, 17 or 18 wherein the electron-reflecting layer is disposed between the optical guiding region and the p-doped cladding region.

20. A laser device substantially as described herein with reference to any one of Figures 4 to 9 of the accompanying Figures.

ABSTRACT

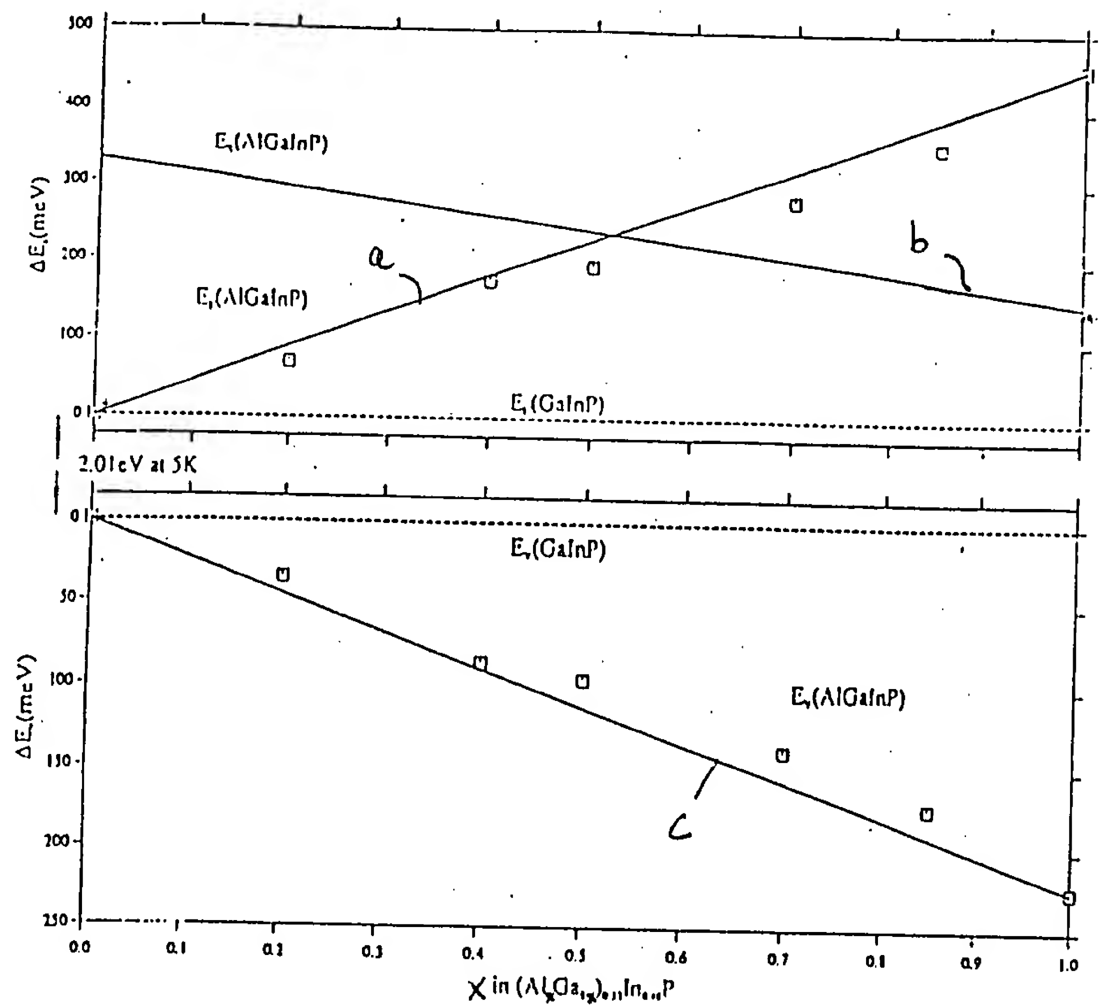
A Semiconductor Laser Device

A separate confinement hetero structure laser device has an optical guiding region (10) and a p-doped cladding layer (11). An electron-reflecting barrier (14) is disposed at the p-side of the device, for example at the interface between the optical guiding region (10) and the cladding region (11). The electron-reflecting barrier (14) has a first electron-reflecting layer (12) for reflecting Γ-electrons and a second electron-reflecting layer (13) for reflecting X-electrons.

The electron-reflecting layers can be strained semiconductor layers. A strain balanced electron-reflecting barrier is formed if one of the electron-reflecting layers (12) is in tensile strain and the other electron-reflecting layer (13) is in compressive strain.

In another feature of the invention, only a single electron-reflecting layer (12) is provided. A reduction in the leakage of X-electrons is obtained by making the X-band of the electron-reflecting layer (12) degenerate with the Γ-band of the optical guiding region (10).

Fig 1



A diagram of the variation of the $Ga_{0.52}In_{0.48}P$/(AlGa)InP heterobarrier height (meV) as a function of aluminium mole fraction in the quaternary alloy assuming a 67:33 band offset ratio.

FIG.2

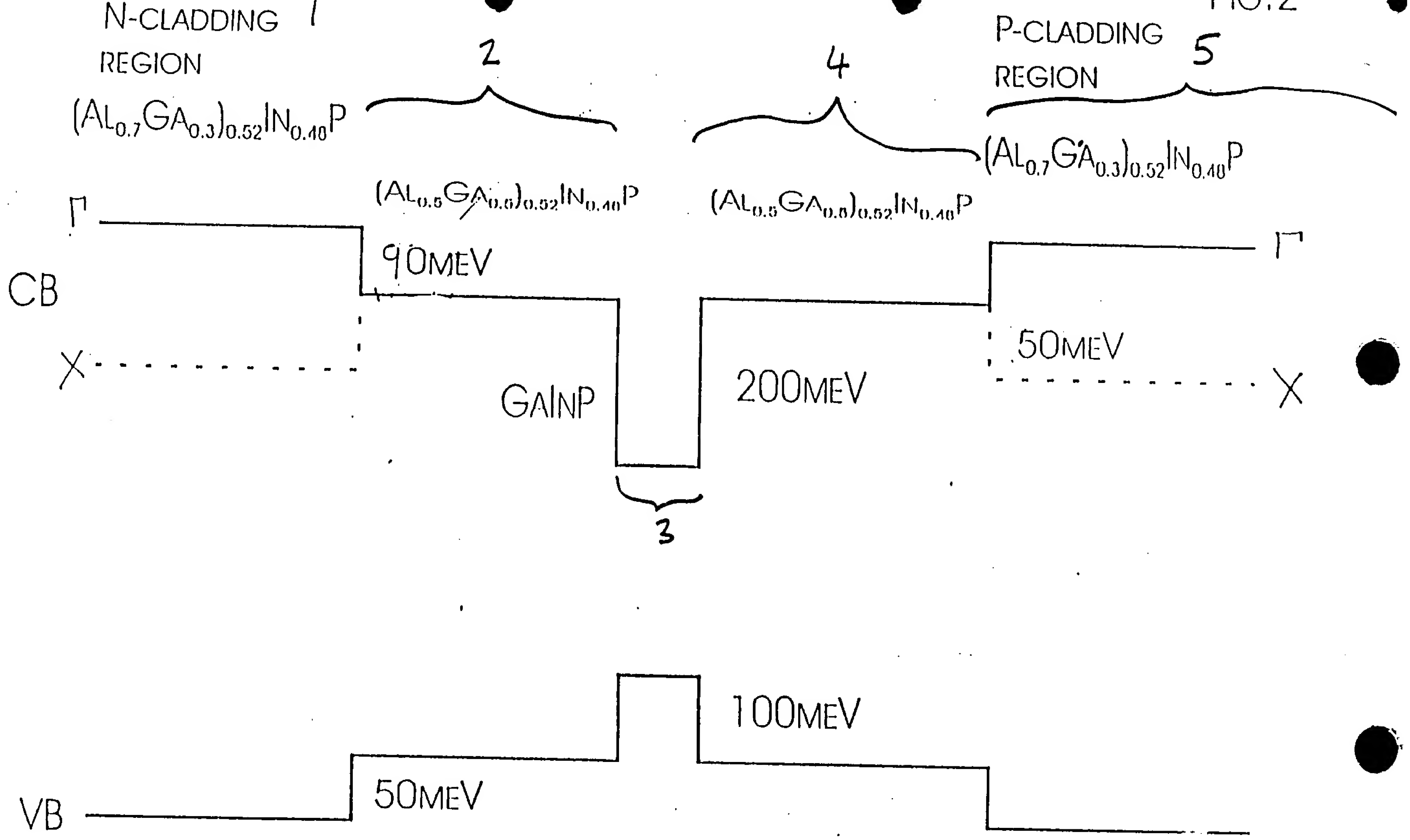

N-CLADDING REGION
1
$(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$
2
$(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$
4
$(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$
P-CLADDING REGION
5
$(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$
Γ
CB
X
90MEV
GAINP
3
200MEV
50MEV
Γ
X
100MEV
50MEV
VB

Fig.3

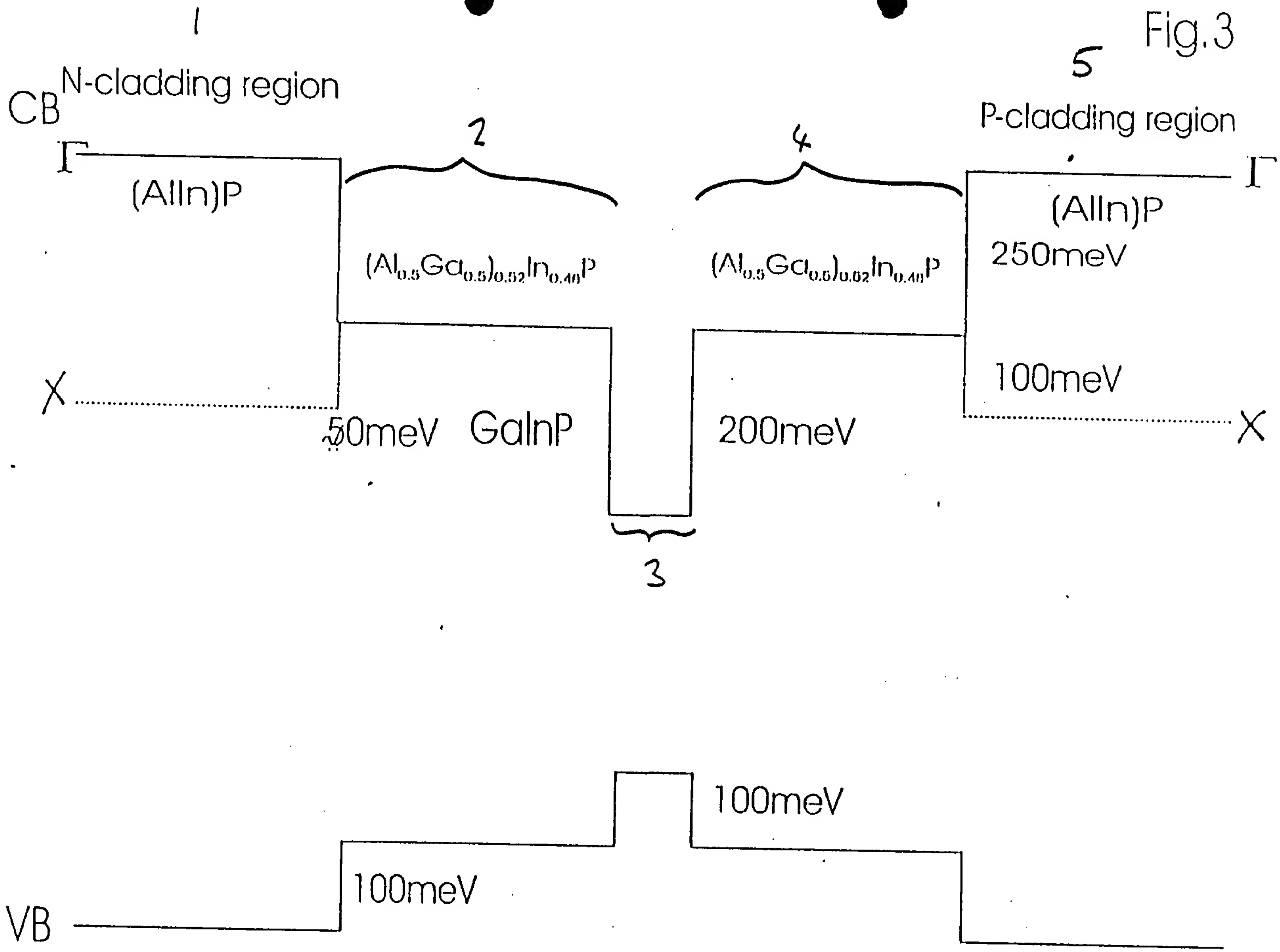
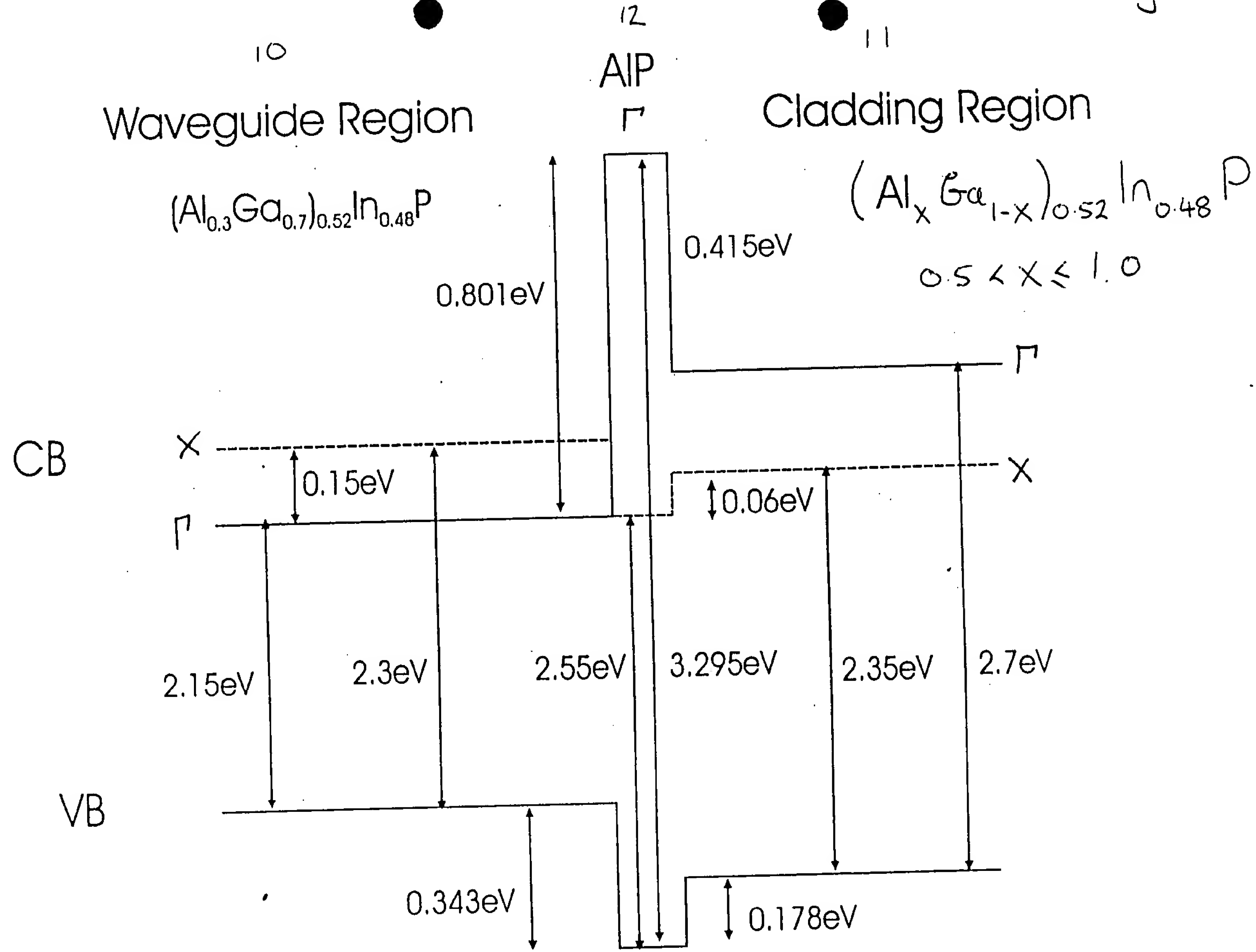
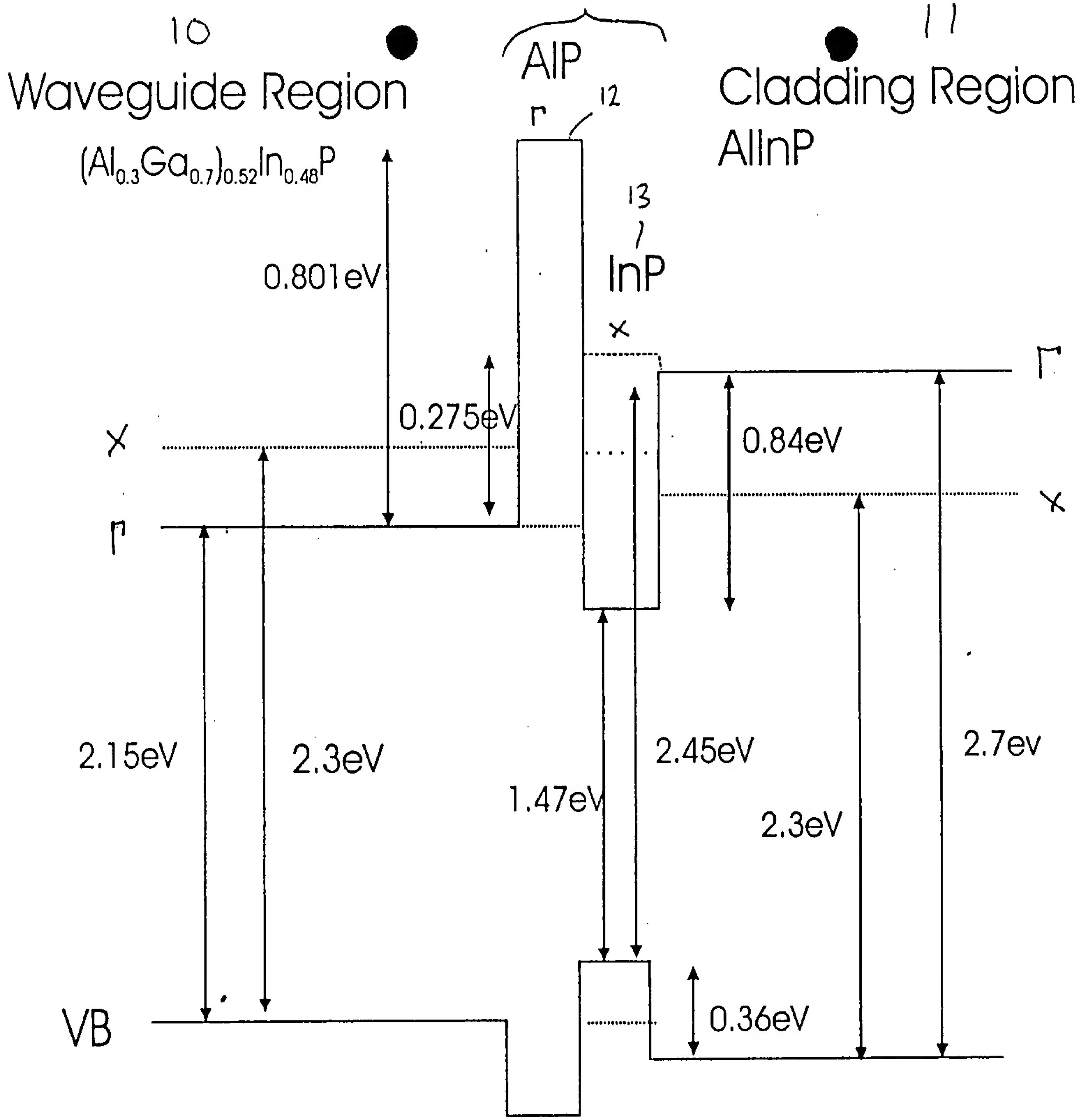

1
CB
N-cladding region
Γ
(AlIn)P
X
50meV
2
$(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$
GaInP
3
4
$(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$
200meV
5
P-cladding region
(AlIn)P
250meV
100meV
Γ
X
VB
100meV
100meV

Figure 4

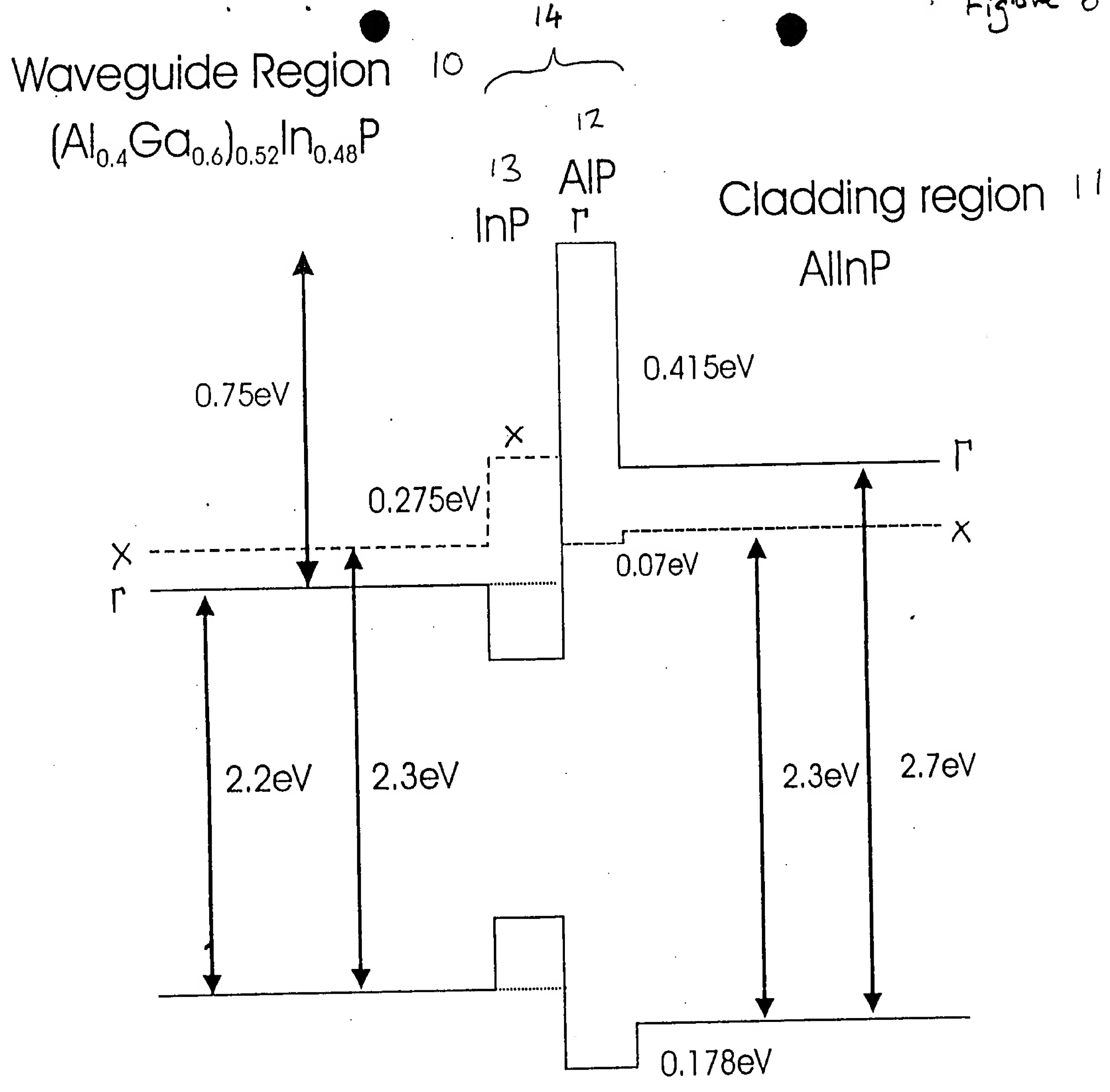


10
12
11
AlP
Γ
Waveguide Region
Cladding Region
$(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$
$(Al_xGa_{1-x})_{0.52}In_{0.48}P$
$0.5 < x \leq 1.0$
0.801eV
0.415eV
CB
X
Γ
0.15eV
0.06eV
2.15eV
2.3eV
2.55eV
3.295eV
2.35eV
2.7eV
VB
0.343eV
0.178eV



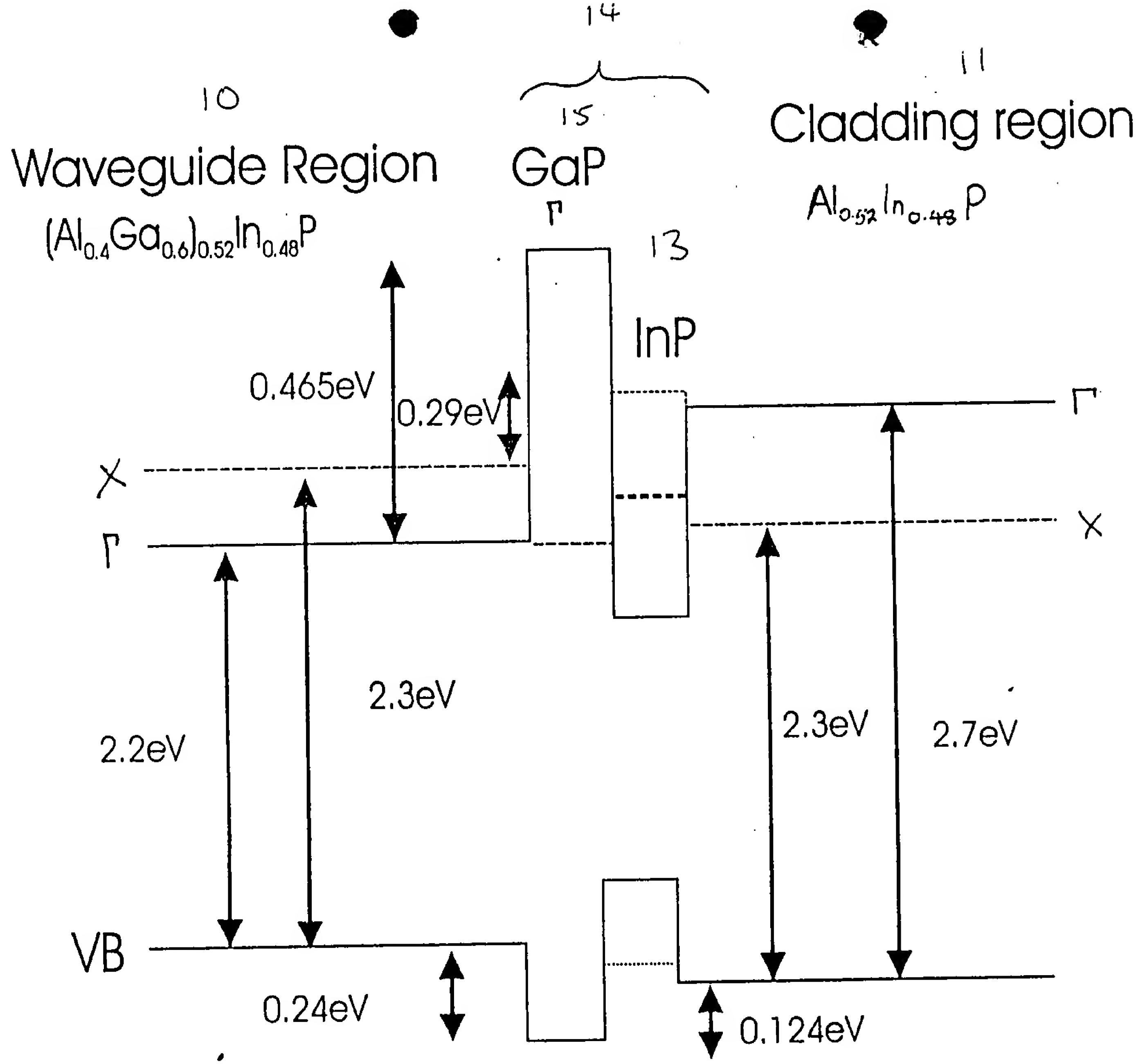
10
Waveguide Region
$(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$
AlP
Γ
12
Cladding Region
AlInP
11
13
InP
X
0.801eV
0.275eV
0.84eV
X
Γ
Γ
X
2.15eV
2.3eV
1.47eV
2.45eV
2.3eV
2.7ev
0.36eV
VB

Figure 6



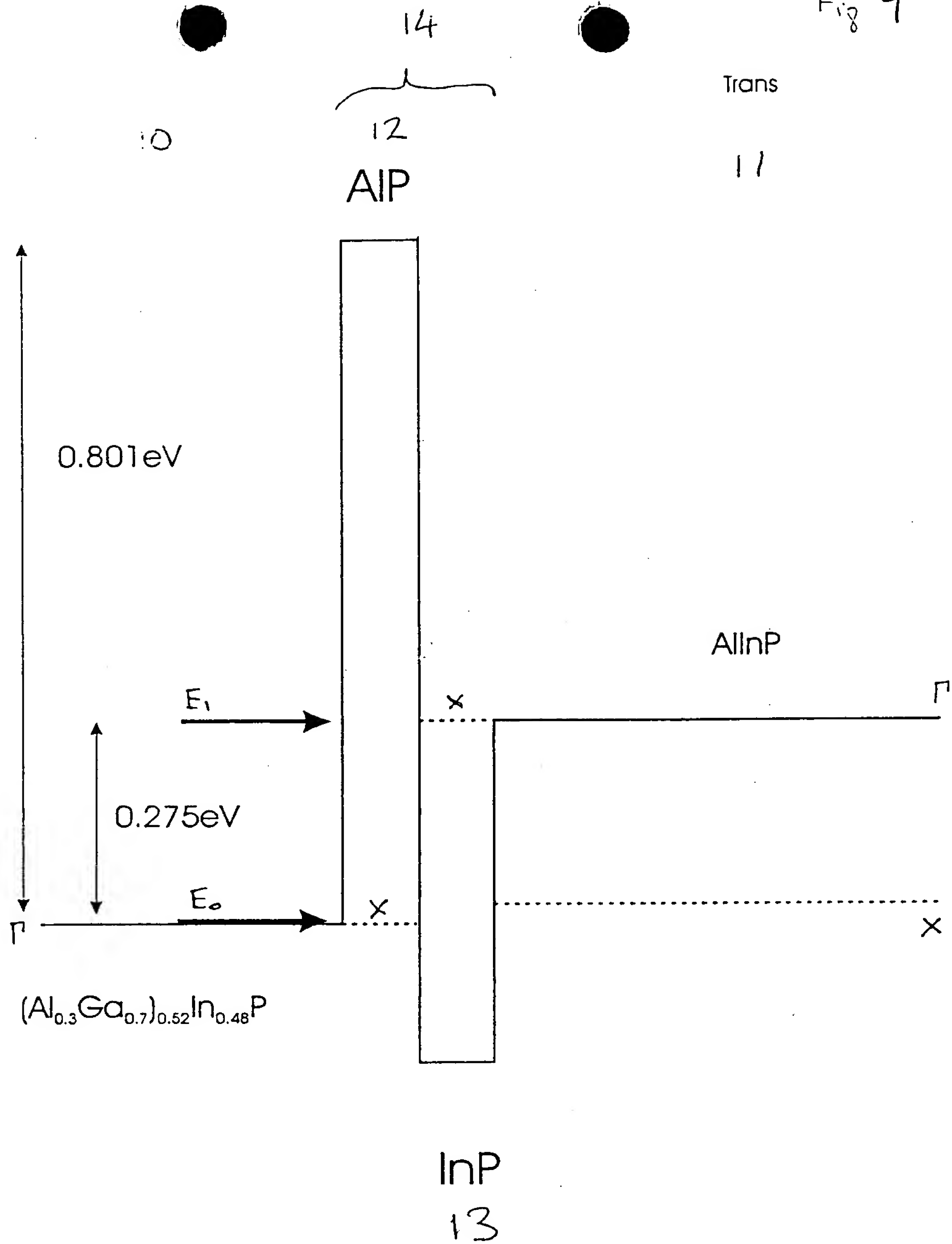
Waveguide Region
10
$(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$
14
12
13
AlP
InP
Γ
Cladding region
11
AlInP
0.75eV
0.415eV
X
0.275eV
Γ
X
0.07eV
X
Γ
2.2eV
2.3eV
2.3eV
2.7eV
0.178eV

Figure 7



10
Waveguide Region
$(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$
14
15
GaP
Γ
13
InP
11
Cladding region
$Al_{0.52}In_{0.48}P$
0.465eV
0.29eV
X
Γ
2.2eV
2.3eV
VB
0.24eV
Γ
X
2.3eV
2.7eV
0.124eV

Fig 9


14
:0
12
AlP
Trans
11
0.801eV
AlInP
E1
x
Γ
0.275eV
E0
X
Γ
X
$(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$
InP
13